NAVY EXPERIMENTAL DIVING UNIT

REPORT NO. 9-95

EVALUATION OF SHERWOOD SCUBA REGULATORS FOR USE IN COLD WATER

J.R. CLARKE AND M. RAINONE

JULY 1995

NAVY EXPERIMENTAL DIVING UNIT

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NEDU tested the breathing effort and susceptibility to freeze-up of two models of Sherwood SCUBA regulators, the Blizzard and the Maximus. Both regulators were tested in -2°C (28°F) salt water, at depths to 60.7 msw (198 fsw). Five examples of each model were tested. The probability of regulator failure was computed from the number of cold induced incidents, and the time to failure for each incident. Under these rigorous conditions, the probability of failure for the Sherwood Blizzard was approximately half that of the Maximus. Furthermore, the Blizzard's breathing effort was consistently lower than the Maximus, especially at low supply pressures. The Sherwood Blizzard should be adequate for dives of up to 40 min duration in sea water temperature to 28°F. Deeper than 100 fsw, only moderate work (RMV no greater than 40 $L \cdot min^{-1}$) should be accomplished.

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GLOSSARY

ANU	Authorized for Navy Use List (NAVSEAINST 10560.2 series)
bar	Metric Unit of pressure conveniently sized for supply pressures. One bar = 100 kPa, or 14.5 psi.
chatter	Pressure oscillations within the mouthpiece of a demand regulator, occurring primarily during inspiration.
cmH_2O	A metric expression of static pressure head. One cmH_2O = 0.01 meters of pure water. In pressure equivalents, 1 cmH_2O= 0.736 torr, 981.8 Pa, or 0.0982 kPa.
flow resistance	A mechanical impedance describing the proportionality between driving pressure and the resulting flow. Units are $cmH_2O \cdot L^{-1} \cdot sec$ or $kPa \cdot L^{-1} \cdot sec$. The average resistance over a tidal breath can be derived from $\overline{P}_V$ and RMV.
fsw	Feet of Seawater, a unit of pressure. One fsw = 0.3063 msw.
J/L	Joules per liter, unit of measure for "Work of Breathing" normalized for tidal volume. One J/L = 1 kPa.
kPa	Kilopascals or newton/m^2, unit of pressure. One kPa ~ 10.2 cmH_2O
msw	Meters of Sea Water. One msw = 3.2646 fsw.
NAVSEA	Naval Sea Systems Command
NEDU	Navy Experimental Diving Unit
psi	Pounds per Square Inch, an English measure of pressure. One psi = 6.895 kPa. 1 bar = 14.504 psi.
$\overline{P}_V$	Volume averaged pressure, or resistive effort, otherwise known by the misnomer Work of Breathing (WOB). A computer derived estimate of total resistive respiratory effort obtained when breathing a regulator with a mechanical breathing simulator.
resistance	see flow resistance
RMV	Respiratory Minute Volume with units of $L \cdot min^{-1}$

INTRODUCTION

The U.S. Navy has a requirement to identify open circuit SCUBA regulators which perform reliably in deep, cold water (58.2 msw (190 fsw), -2°C (28°F)). To this end, NEDU was tasked[1] to test and evaluate production models of commercially available open circuit SCUBA regulators to determine those which best meet the U.S. Navy's requirement. This is a report on Sherwood regulators. Reports on other cold-water regulators that NEDU has tested will be forthcoming.

Sherwood (Lockport, NY) provided two models for evaluation; the Maximus (SRB3600) and the Blizzard (SRB3900). The first stage on the Maximus is externally adjustable with a flow-by piston with moving orifice balancing and a positive air purge (dry air bleed). The second stage (SRB3602) is a downstream design with an adjustable diaphragm. The Blizzard, designed as a cold water regulator, uses the same first stage as the Maximus (SRB3601). The Blizzard second stage incorporates a heat sink located over the exhaust outlet to transfer heat from the diver's breath to the lever support assembly. This feature is not found in the Maximus. Other feature comparisons are : (Blizzard) - Triax hard plastic front cover and exhaust tee, 31 inch hose assembly, over the shoulder hose entry into the second stage; (Maximus) - soft second stage cover with integrated exhaust tee, 40 inch hose assembly, under the arm hose with a swivel entry for the 40 in. hose.

For regulators designed for use in relatively warm water (>37°F), the primary criterion by which the regulators are judged during unmanned testing is their ability to meet the Performance Goal Standards[2] for volume-averaged pressure ($\overline{P}_V$) or resistive effort. *(Resistive effort was formerly termed Work of Breathing (WOB). What has long been measured as WOB (with units of Joule/liter) is not actually a measure of Work (which has units of Joules).* For diving under polar ice, however, a more important consideration than breathing effort is resistance to freeze-up. In modern regulators, freeze-up is usually manifested as free-flow due to either a second stage failure, or first stage loss of intermediate pressure control. On rare occasions the first stage can fail with complete blockage of gas flow. Since freeze-up is a potentially life-threatening occurrence, we placed primary emphasis on regulator freeze-up susceptibility, with secondary emphasis on $\overline{P}_V$.

METHODS

Regulators

The regulators supplied to NEDU by Sherwood were 1995 models, with consecutive serial numbers (R509964-R509968, Maximus; R507634-R507638, Blizzard). They were set up according to Sherwood instructions and bench tested prior to the initial cold water exposures.

Environmental Control

The test regulators were submerged in brine-filled arks with water temperature maintained at -2.2°C ± -0.5°C (28°F to 31°F). The brine mixture was prepared with tap water and Instant Ocean® salt mixture (Aquarium Systems, Mentor, OH). The salinity of the brine solution was approximately 45 parts per thousand to prevent ice formation on the heat exchanger coils and loss of temperature control. Salinity was measured by the refractive index of the brine using an automatic temperature compensated hand refractometer (Model 10419, Reichert Scientific Instruments, Buffalo, NY). The water content in the high pressure air supply was measured by a phosphorous pentoxide (P_2O_5) detector system, and was found to be 23 ppm, translating to a -65.5°F dewpoint.

"Exhaled" air from the breathing machine was heated and humidified such that the gas temperature measured at the chrome tee (connected to the mouthpiece of the second stage regulator) ranged between 10° and 20°C. Under steady-state conditions, the exhaled temperature (T_{ex}) varied with depth, tending to be higher at the greater depths.

Breathing Simulator

A computer controlled electro-mechanical breathing simulator (Battelle, Columbus, OH) ventilated each regulator at a range of respiratory minute ventilations (RMV) of 22.5 to 90 $L \cdot min^{-1}$, thus emulating varied diver work rates. Supply pressure to the first stage was maintained at 103.4 bar (1500 psi) for one set of tests, then reduced to 34.5 bar (500 psi) for another set. This procedure was in accordance with NEDU Test Plan 93-21, except that in this instance the regulators were warmed and dried before repeating the cold water exposure with 34.5 bar supply pressure[3]. Recordings of pressure-volume loops were taken at 10 msw (33 fsw) increments. Test depths ranged from 0 to 60.7 msw (0 to 198 fsw). Testing at a specific RMV/depth parameter was terminated if inhalation or exhalation pressure exceeded 4 kPa, the working limits of the pressure transducers currently used in the Experimental Diving Facility.

Statistics

Descriptive statistics were used to obtain the mean and standard deviation of the resistive effort data. To describe $\overline{P}_V$ (WOB) as a function of depth and RMV, nonlinear parameter estimation using the method of least squares was employed. Nonlinear estimation was also used to describe the various probabilities of regulators successfully completing tests. Statistical significance was established at $P < 0.05$. Differences between the $\overline{P}_V$ for the Blizzard and Maximus regulator were determined by either nonlinear or multiple linear regression.

Freeze-Up Dive Profiles

NEDU routinely uses a fixed depth, worst case protocol for evaluating freeze-up susceptibility, for reasons described in Appendix A. This consists of diving the regulator to 60.7 msw (198 fsw) and breathing it at an RMV of 62.5 $L \cdot min^{-1}$ for 30 minutes. This run is repeated at 40.4 msw (132 fsw) and 10.1 msw (33 fsw). For the current series of tests we also used a severe bounce dive protocol with a dive to 58.2 msw (190 fsw) for 20 min with an RMV of 50 $L \cdot min^{-1}$. This was followed by five minute decompression stops at 40, 30, 20, and 10 fsw with the same RMV. This profile supposedly follows the longest non-exceptional exposure table for the new probabilistic air algorithm[4] .

Failure Probability Determination

For freeze-up susceptibility tests, both the number of regulators freezing and the time at which they froze is important. Those results can be empirically combined in the following manner.

$$P_f = \sum_{i=1}^{n} \left(\frac{n^{-1} \cdot E_i}{t_i^k} \right)$$

where P_f is the probability of failure (ranging between 0 and 1), n is the number of regulators, E is a binary event equal to 0 if there is no failure and 1 if the regulator fails, t is the time to failure in minutes, and k is an empirical constant = 0.3, chosen to provide reasonable probabilities. By NEDU convention, n = 5. If all 5 regulators freeze after 1 min, then

$$P_f = \left(\frac{0.2 \cdot 1}{1^{.3}} + \frac{0.2 \cdot 1}{1^{.3}} + \frac{0.2 \cdot 1}{1^{.3}} + \frac{0.2 \cdot 1}{1^{.3}} + \frac{0.2 \cdot 1}{1^{.3}} \right) = 1.0$$

If no regulators fail, then $P_f = 0$. If 2 freeze, one at 18 min and one at 28 min, then

$$P_f = \left(0 + 0 + 0 + \frac{0.2 \cdot 1}{18^{.3}} + \frac{0.2 \cdot 1}{28^{.3}} \right) = 0.158$$

If 3 regulators froze at 5, 6, and 10 min into the runs, then $P_f = 0.34$. When ranking the desirability of various cold water regulators, a regulator with a P_f of 0.158 would be preferred over one with a P_f of 0.34.

The above empirical probability estimation is nothing more than a way of quantitatively comparing various regulators. It does not estimate the actual probability of freeze-ups during an open water dive. That probability is dependent upon the duration of the dive relative to the expected time of regulator freeze-up.

Resistive Effort

$\overline{P}_V$ levels are a computer derived estimate of total respiratory effort obtained when breathing a regulator with a mechanical breathing simulator, measured in kPa (or in more cumbersome terms, joules per liter, J/L). $\overline{P}_V$ averages were derived from the mean of tests on up to five individual regulators for each model.

RESULTS

Freeze-Up Susceptibility

All regulators that froze during the freeze-up susceptibility tests, did so at the deepest depth, either 60.7 msw (198 fsw) or 58.2 msw (190 fsw). One of the five Maximus regulators failed to control intermediate pressure during both the fixed and bounce dive profiles. For purposes of computing P_f this dive was expressed as a failure within 1 min. The four other regulators began to free flow at 5, 6, 11, and 16 min into the 30 min test at 60.7 msw. For the 40 min bounce dive profile, one regulator made it to test termination. The others free-flowed at 8, 15, and 38 min.

All Blizzard regulators tracked over-bottom pressure correctly. Two regulators completed the 30 min fixed profile dive without incident. Three free-flows occurred at 7, 7, and 14 min. Using the bounce profile, three regulators completed the entire 40 min test. Two regulators free-flowed at 9 min and 26 mins. The resulting P_fs for both regulators are given in Table I for both test profiles.

Table 1. Probability of failure (P_f) for Blizzard and Maximus regulators.

Blizzard (fixed)	Maximus (fixed)	Blizzard (bounce)	Maximus (bounce)
0.314	0.625	0.179	0.463

Regardless of the dive profile, the computed probability of failure was about twice as high for the Maximus as for the Blizzard, with all failure modes being free-flow. The probability of failure in the bounce dive profile was a little less than in the fixed dive profile. However, in keeping with the probabilistic nature of freeze-up (discussed in Appendix A), one Blizzard regulator that froze in the bounce profile did not freeze in the fixed profile.

Resistive Effort

The mean resistive efforts for both regulator models are shown in Figures 1 and 2. The horizontal lines in each panel mark the NEDU performance goal[2] for SCUBA regulators, 1.37 kPa. Some runs were aborted by the operators to protect the test instrumentation whenever the inhalation or exhalation pressures exceeded 4 kPa. The plotted means represent the average for all completed runs. Tests on the Maximus were consistently aborted under 15 conditions; 8 at 103.4 bar supply pressure and 7 with a 34.5 bar supply pressure. On the other hand, Blizzard runs were only aborted 9 times, 5 at 103.4 bar supply pressure and 4 at 34.5 bar.

Typically, the $\overline{P}_V$ of greatest interest is that at an RMV of 62.5 L·min^{-1} at the deepest depth. At a depth of 60 msw and an RMV of 62.5 L·min^{-1}, no data was obtained from the Maximus at either supply pressure due to high ventilatory pressures (> 4 kPa). On the other hand, Blizzard data was obtained from 4 out of 5 regulators. The mean $\overline{P}_V$ for those four regulators at 103.4 bar supply pressure was 2.50 ± 0.58 kPa (mean ± 1 SD).

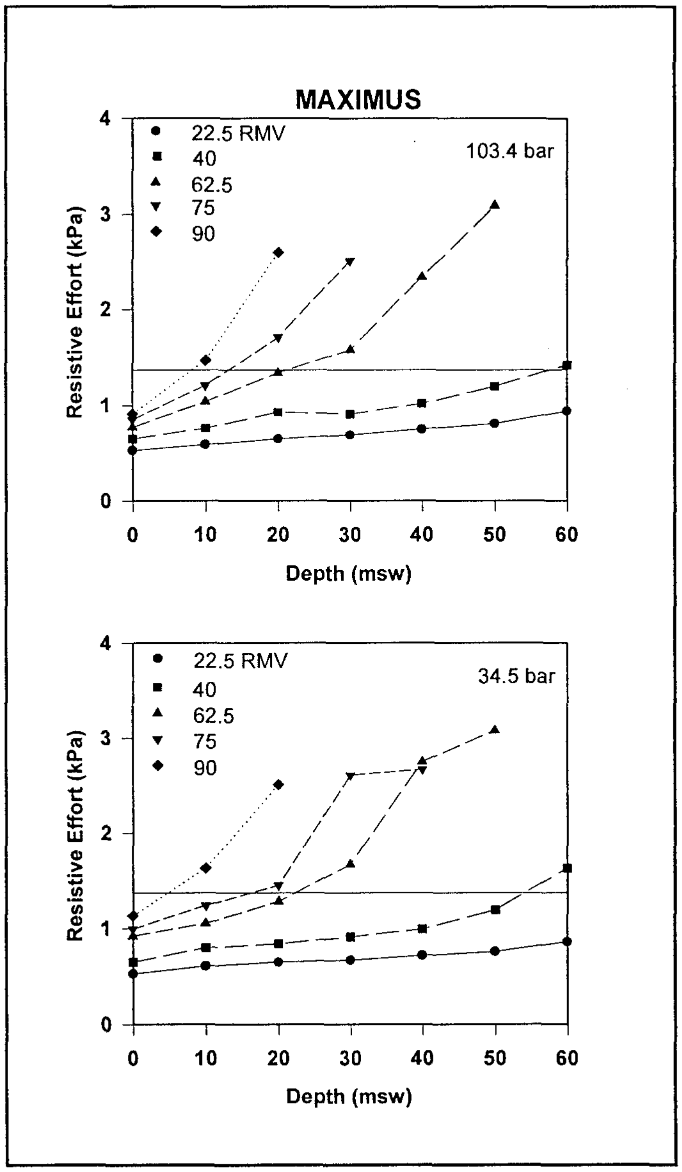

Figure 1. Mean resistive effort (WOB) for Maximus regulators at moderate and low supply pressure.

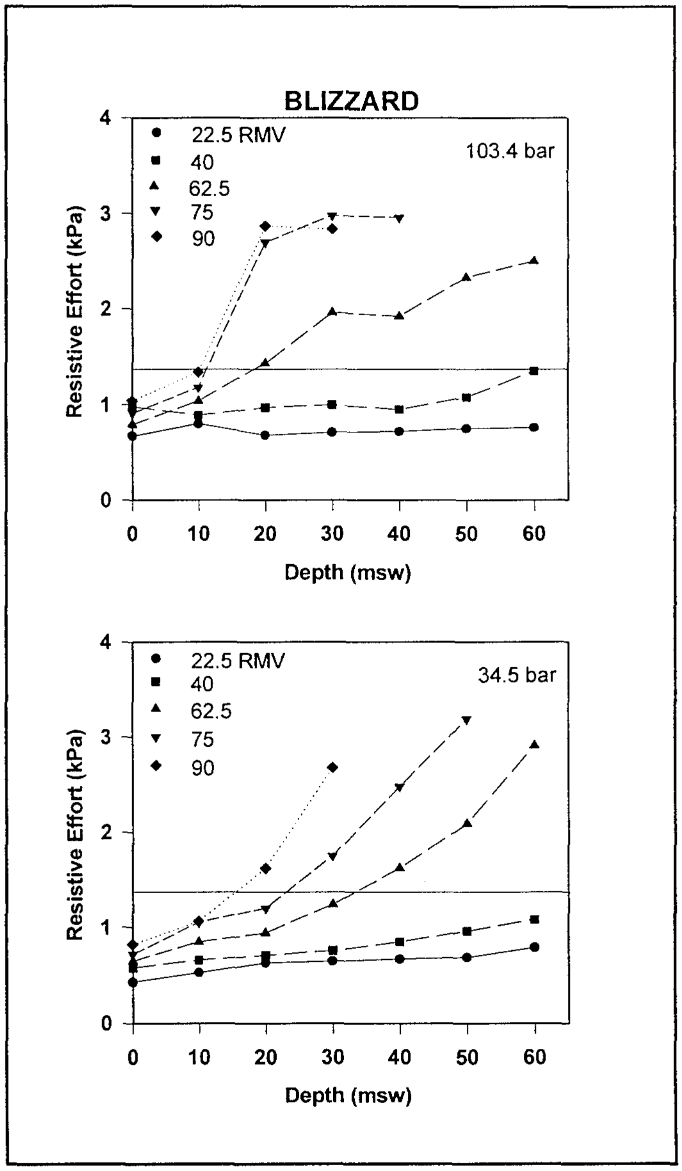

Figure 2. Mean resistive effort (WOB) for Blizzard regulators at moderate and low supply pressure.

Breathing Resistance

It was recently shown[5] that resistive effort ($\overline{P}_V$) can be transformed into breathing resistance. Since $\overline{P}_V$ is an average pressure, dividing it by ventilation yields an average resistance (R), an average over the entire tidal breath.

$$R = \frac{4\,\overline{P_V}}{\pi \cdot \omega \cdot V_T}$$

In the above equation V_T is tidal volume and ω is the respiratory frequency in radians·sec^{-1}. Since $\omega = 2 \cdot \pi \cdot f$, where f is the respiratory frequency in Hz, and because $RMV = f \cdot V_T$, taking into account the conversion factor of 60 sec/min, then the above equation reduces to:

$$R = \frac{2\,\overline{P_V}}{\pi^2 \cdot RMV}$$

Plots of breathing resistance (with units of $cmH_2O \cdot L^{-1} \cdot sec$) versus depth (top panel) and RMV (bottom panel) are shown for the Maximus in Figure 3 and the Blizzard in Figure 4. Each data point represents the mean resistance of 5 regulators. Unlike Figures 1 and 2, the results of partially completed runs where 1 or more regulator tests were aborted, are not included. When plotted against RMV, the average resistance drops, at least initially, presumably due to the second-stage venturi.

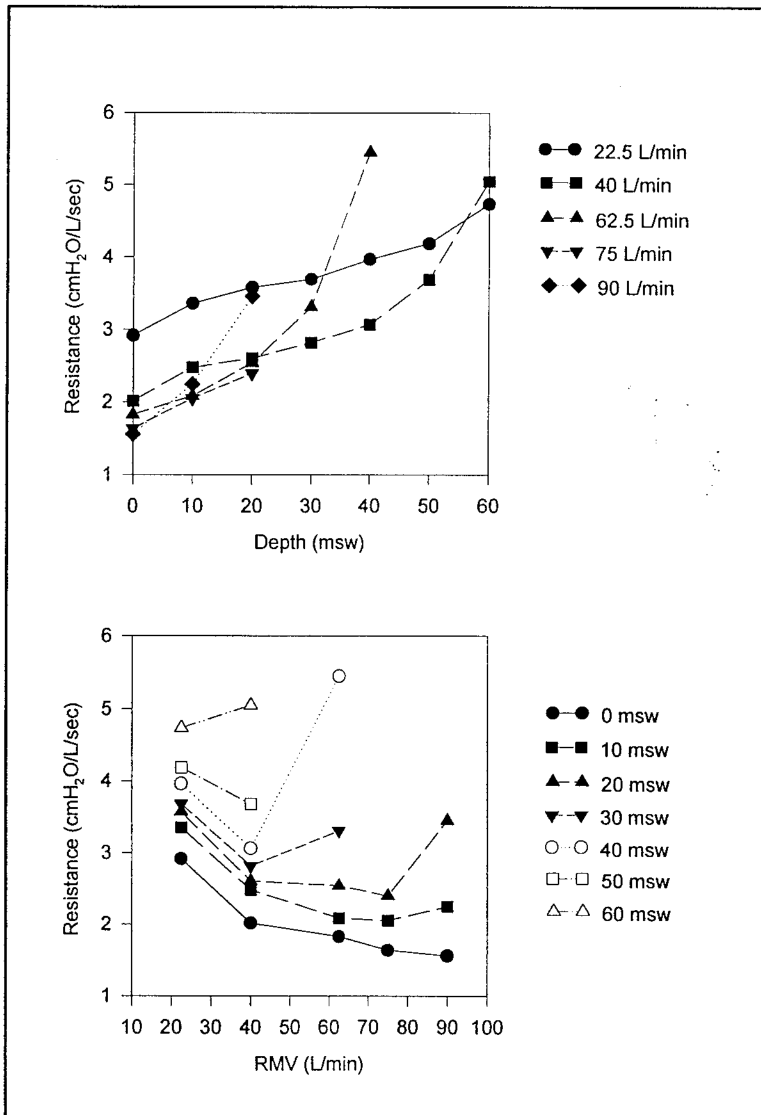

Figure 3. Mean breathing resistance of the Maximus regulators at low supply pressure (34.5 bar).

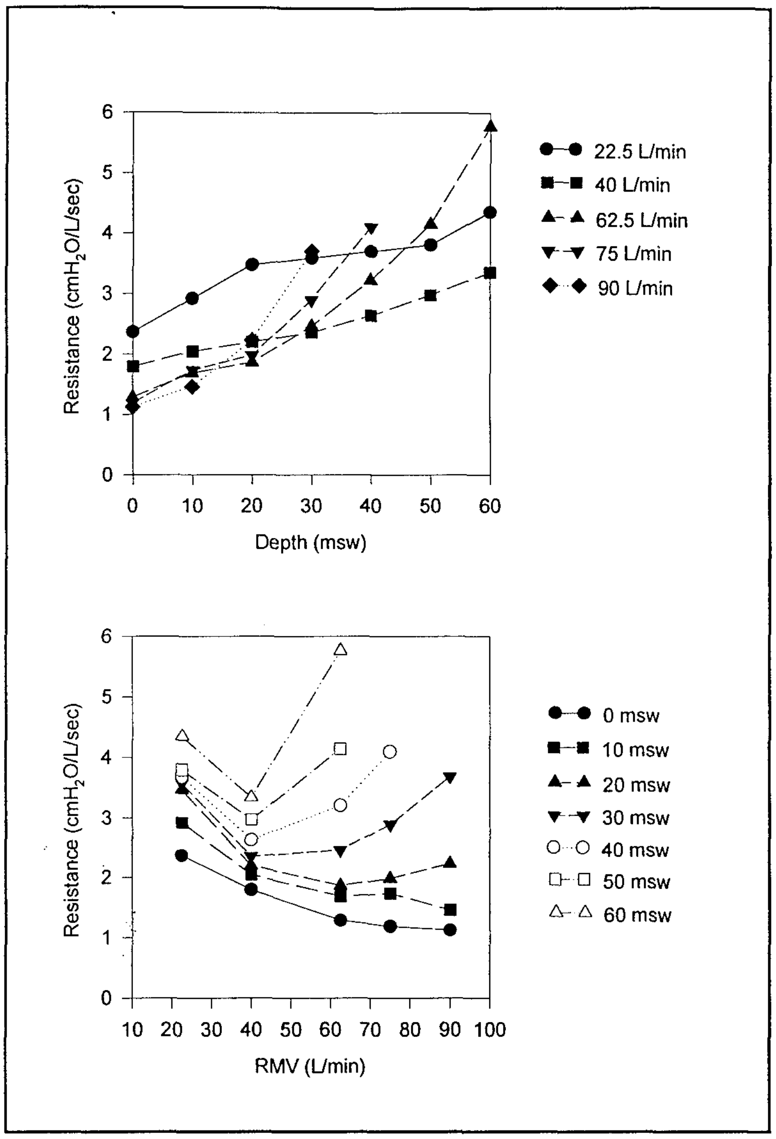

Figure 4. Mean breathing resistance of the Blizzard regulators at low supply pressure (34.5 bar).

From the lower panel in Figure 4 we see that for the Blizzard at depths of 30 msw or deeper, breathing resistance is minimized at a ventilatory rate of 40 L·min^{-1}. The Maximus shows a similar minimum at 40 L·min^{-1}, but only between 30 and 50 msw.

Event Incidence in Resistive Effort Tests

The measurements of resistive effort presented another means for comparing the reliability of the Blizzard and Maximus regulators. The primary purpose of these tests was to describe the breathing effort of the respective regulators. However, two events could hamper these measurements. As previously mentioned, one was excessively high ventilatory pressures. The other cause for an aborted run was regulator free flow. The two events were considered of equal importance since both could be due to the effects of cold water.

The event incidence rate was an observed probability, thus it varied from 0 to 1.0. Since five samples of each regulator were tested under each condition of depth and RMV, the event probability or incidence rate varied in increments of 0.2. If 2 out of 5 regulators failed to complete the effort test, the failure incidence was 0.4. If all five failed the test, then the incidence was 1.0.

Figures 5 and 6 are plots of the event incidence, on the vertical axis, for the Blizzard and Maximus regulators at 103.4 bar supply pressure. One horizontal axis, the test sequence, represents the order in which tests were conducted on each regulator. Each test began at 190 fsw with an RMV of 22.5 $L \cdot min^{-1}$. RMVs were increased sequentially through 90 $L \cdot min^{-1}$, and then the chamber was brought up to the next shallower depth before the RMVs were repeated. Consequently, tests at the surface and 90 $L \cdot min^{-1}$ were the last runs conducted. For both regulators, the entire test sequence took between 1 hr and 1 hr 15 min. Therefore, each sequence number represents an interval of about 2 min.

Mass flow, with units of grams per liter (g/L), is shown on the second horizontal axis. Mass flow is defined as:

$$\dot{M} = \rho \cdot \dot{V} \cdot \frac{P_{amb}}{P_0}$$

where ρ is gas density at 1 ATA and 0°C, $\dot{V}$ is ventilation (RMV) in $L \cdot min^{-1}$, and P_{amb} is ambient pressure in absolute units. P_0 is the absolute pressure at 1 ATA, a factor required to generate a dimensionless pressure ratio. Mass flow rate reflects the mass of gas flowing through the regulator each minute.

Figures 5 and 6 reveal marked differences between the event probabilities in the two regulators. For the Blizzard, the event probability increased monotonically with mass flow and with test sequence. That is, both mass flow and time strongly influenced the probability that Blizzard regulators did not make it through the entire testing sequence. The event incidence for Blizzard regulators began to slowly increase at mass flow rates greater than 350 $g \cdot min^{-1}$. Mass flows of approximately 600 $g \cdot min^{-1}$ were required before the Blizzard regulators consistently produced high pressures during the resistive effort tests. Maximus regulators, on the other hand, made an abrupt transition from all regulators completing the tests (0 failures) to no regulators completing (5 failures, failure incidence = 1.0) as mass flow increased beyond 400 $gram \cdot min^{-1}$.

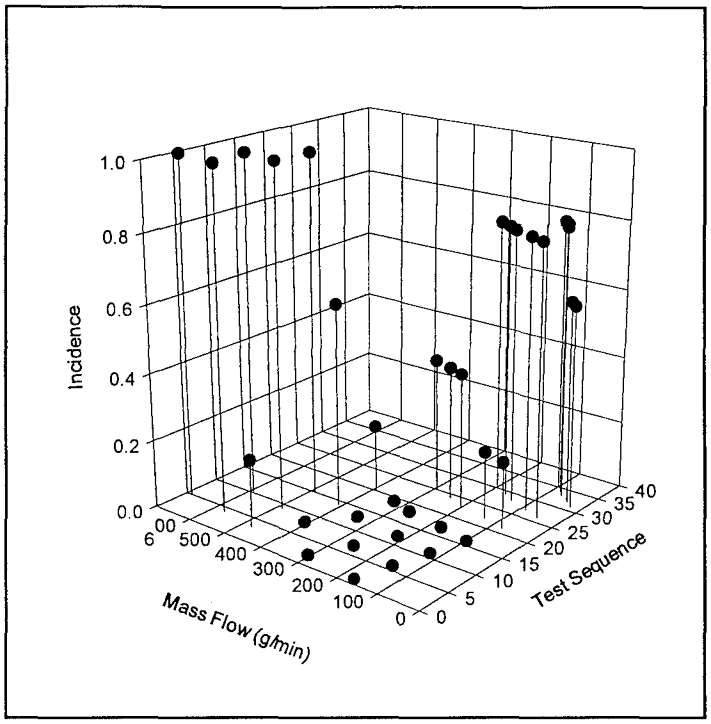

Figure 5. Event incidence for Sherwood Blizzard regulators (103.4 bar supply).

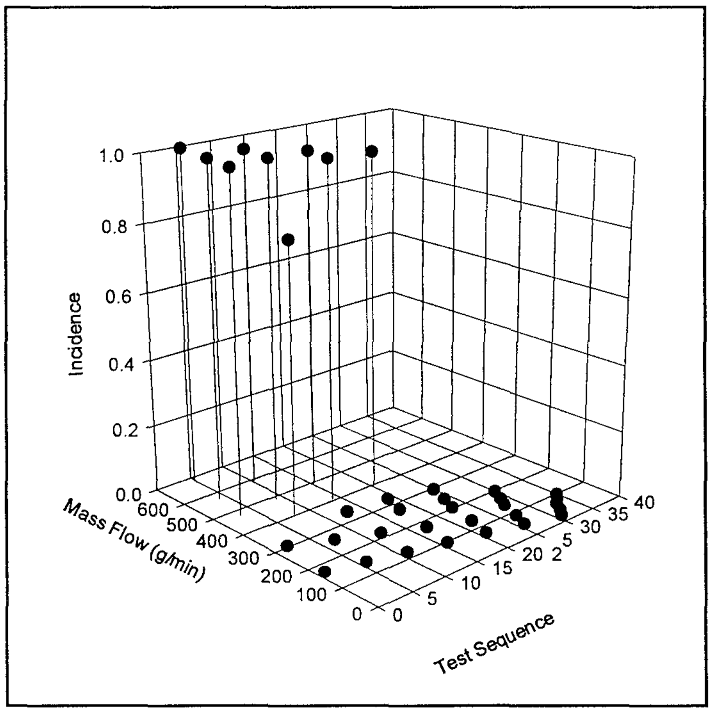

Figure 6. Event incidence for Sherwood Maximus regulators (103.4 bar supply).

The test sequence (time) was not an important factor for the Maximus, whereas it clearly was for the Blizzard.

Modeling Event Incidence

In making predictions about future regulator performance, it is useful to have a model of past regulator performance. The sudden transition in the Maximus performance at high mass flow rates was difficult to model mathematically. However, the Blizzard performance was better behaved, and thus the event probability was modeled as follows:

$$P_{event} = 1 - e^{-(risk)}$$

where

$$risk = (a \cdot sequence)^{b} + (c \cdot massflow)^{d}$$

The four parameters for the above model were estimated from nonlinear regression. They were:
$a = 0.0356 \pm 0.0012$, $b = 4.1002 \pm 0.8299$, $c = 0.0021 \pm .00004$, and $d = 14.314 \pm 6.380$ (best estimate ± standard error). The three dimensional shape of that function is seen in Figure 7. The graph is oriented in the same manner as Figure 5, with the top surface representing an event probability of 1.0.

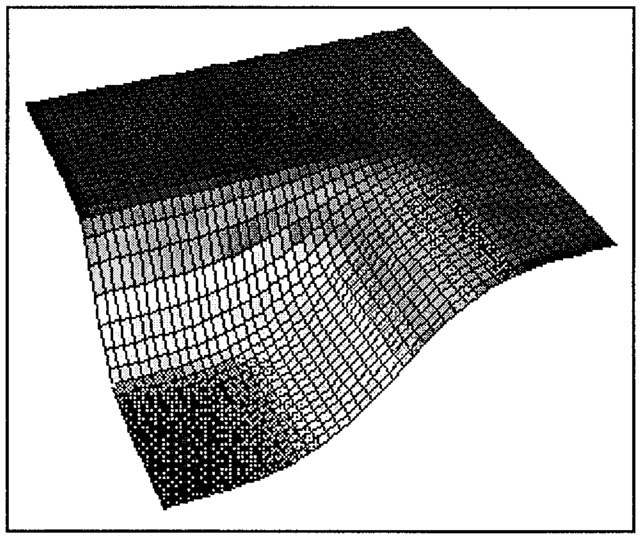

Figure 7. Modeled relationship between event incidence and both test sequence number and mass flow.

Chatter

Both models of regulators were susceptible to occasional but vigorous chatter. When deep, the Blizzard would usually, but not always, chatter during just the beginning of inspiration. At depths of 20 msw or shallower, very pronounced chatter frequently occurred throughout inspiration. The magnitude of chatter, as evidenced by total harmonic distortion (THD), varied unpredictably. For instance, at a depth of 60.7 msw, the average THD for one Blizzard regulator was 0.155 at an RMV of 22.5 $L \cdot min^{-1}$, was 0.453 at 40 $L \cdot min^{-1}$, and dropped back down to 0.116 at 62.5 $L \cdot min^{-1}$.

The Maximus tended to have large cracking pressure peaks at deeper depths which seemed to be associated with a reduction in chattering. We did not attempt a statistical comparison of the chattering tendency of the two regulators.

DISCUSSION

Both the bounce dive and NEDU fixed depth test profiles for freeze-up susceptibility demonstrated that the Sherwood Maximus was roughly twice as likely to freeze-up as the Blizzard. During the resistive effort determinations, the Maximus consistently produced catastrophically high pressures (>4 kPa, 40 cmH_2O) at much lower mass flow rates (400 $g \cdot min^{-1}$) than did the Blizzard (600 $g \cdot min^{-1}$), as seen in Figures 5 and 6.

Even though the resistive effort studies were primarily examining breathing resistance, they did occasionally induce free flow due to freeze-up. They are thus an adjunct to the standard freeze-up evaluation. However, the problem with using the resistive effort studies as a freeze-up evaluation is that flow is intermittent during those tests. The breathing machine is stopped for 30 sec to a minute between each test sequence. It is not known how this periodicity might effect the freeze-up probability. On the other hand, taken at face value, those results suggest that the Maximus may tolerate long duration (>1 hr), low mass flow (shallow, low work) dives with a lesser chance of free flow than does the Blizzard.

The above observation is unlikely to be of any operational significance, however. SCUBA dives in -2°C water are rarely lengthy, even if they are shallow dives. This is especially true for low work dives where a diver produces relatively low amounts of body heat. Therefore, the slowly increasing risk of free flow of the Blizzard after an interval of 1 hour is probably unimportant.

The Maximus regulator is frequently used by Antarctic scientific divers with only a 2-3% failure incidence. A recent draft report[6] describes a series of 36 working dives occurring near McMurdo Station at depths between 21 and 36 msw (70 and 118 fsw) with bottom times ranging from 20 to 35 min. Water temperature was between -1.8° and -1.9° C. Work rates were very low, with air consumption rates of 14 to 17 $L \cdot min^{-1}$. By calculation, the mass flow rates for these dives would not have exceeded 75 $g \cdot min^{-1}$. Therefore, from our test results (Figures 5 and 6) we would anticipate few eventful dives with either of the Sherwood regulators.

On the other hand, military dives may be both deep and involving hard work. Unfortunately, we have no data on such open water dives to compare to our test results. Nevertheless, all of our tests suggest that for high mass flow dives (i.e., deep dives with high RMVs), the Sherwood Blizzard will have considerably fewer problems than the Sherwood Maximus.

Comparison with Approved Regulator

There is only one regulator currently approved for use by the US Navy in cold water (below 37° F). Figure 8, analogous to Figure 5, is a plot of event incidence found in that regulator during measurements of resistive effort. There were no events at all. The freeze-up probability (P_f) for the approved regulator was 0.074 when exposed to the 30 min fixed dive profile, compared to a P_f of 0.314 for the Blizzard and 0.625 for the Maximus.

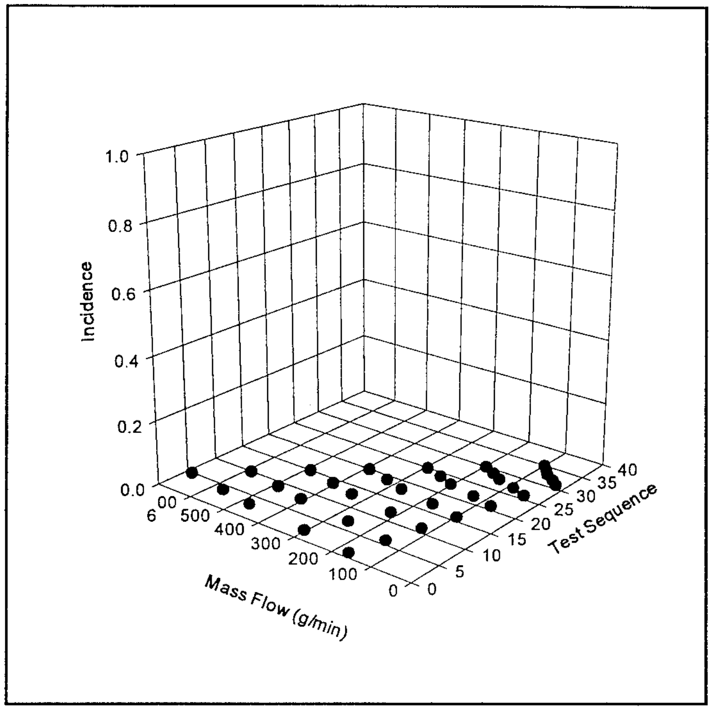

Figure 8. Event incidence for an approved cold water regulator (103.4 bar supply).

Limit of Usefulness

Although the approved regulator outperforms the Sherwood regulators during severe service, from Figure 5 we see that the Sherwood Blizzard performed without incident up to mass flow rates of 400 $g \cdot min^{-1}$ and durations to about 40 minutes (test sequence of 20). A mass flow rate of 400 $g \cdot min^{-1}$ allows an RMV of 62.5 $L \cdot min^{-1}$ to be supported without catastrophic results down to 132 fsw, and an RMV of 40 $L \cdot min^{-1}$ down to 190 fsw. The Blizzard should therefore support the majority of expected cold water dives. Nevertheless, the resistive effort of the Blizzard (Figure 2) is such that it would be advisable to limit RMVs to 40 $L \cdot min^{-1}$ at depths of 30 msw (~100 fsw) and deeper.

Although the Maximus does well under these same constrained conditions, we do not recommend it, at least in the form tested. Should a diver experience difficulty and require high flow rates, the $\overline{P}_V$ of the Maximus (Figures 1 and 3), and its relatively large freeze-up susceptibility (Table 1) would put the diver at greater risk than would the Blizzard.

RECOMMENDATION

On the basis of the above tests, the Sherwood Blizzard regulator is recommended to be authorized for Navy use (ANU) in water temperatures as cold as 28°F to a maximum depth of 100 fsw with bottom time not to exceed 40 minutes. NEDU does not recommend that the Sherwood Maximus be authorized for Navy use in cold water.

No SCUBA regulator can completely eliminate the risk of freeze-up. Those factors that increase risk are depth, time, and flow rate. Consequently the safest dives will be shallow, short duration, low work rate dives. The more extreme the dive conditions, the greater the risk of a freeze-up incident.

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Appendix A: Justification for NEDU Testing Procedures for Cold Water Regulators

SCUBA regulator freeze-up is an event governed by the rules of probability. It is dependent upon the probability of water gaining entry to the inside of a regulator second stage (P_{we}), and the probability of low temperatures in the second stage (P_{lT}). P_{lT} is in turn governed by a balance between adiabatic processes producing regions of low temperature, and heat flux towards those cold regions. In general mathematical terms;

$$P_f = P_{we} \cdot P_{lT} \qquad (1)$$

where P_f is the probability of regulator failure due to freezing. The probability of second stage water entry (P_{we}) is a function of exhaust valve design (controlling the ease of exhaust valve inversion) and the magnitude of negative pressures. Negative pressures are in turn generated by high ventilatory rates and high gas densities related to depth when a diver works against inspiratory resistance (another feature of regulator design). Therefore, $P_{we} = f(\dot{V}E$, D, and $M_{1...n})$ where $\dot{V}E$ is ventilatory rate, D is depth, and M is a number of manufacturer determined parameters (e.g., M_1 = exhaust valve leakage pressure, M_2 = inhalation resistance, etc.).

Adiabatic gas expansion is not strongly influenced by anything other than the volume expansion occurring across various orifices and valves (Equation 2). T_f, the expanded volume temperature in absolute units (K), is given by

$$T_f = T_i \cdot \left(\frac{V_i}{V_f}\right)^{\gamma - 1} \qquad (2)$$

where T_i is the pre-expansion temperature, V_i and V_f are the respective gas volumes, and γ is the ratio of specific heats for constant pressure and constant volume ($\gamma = 1.4$ for air). However, the balance between adiabatic cooling and the countering heat flow is controlled by $\dot{V}E$, and also by certain design features.

Based on the foregoing we can hypothesize an instantaneous risk function for any particular regulator model:

$$r(t) = (a \cdot D) \cdot (b \cdot Ve) \cdot \left(\prod_{i=1}^{N} c_i \cdot M_i\right) \qquad (3)$$

where a, b, and c are various, and generally unknown, proportionality constants. Those constants are constant in only a very limited sense, however. They are expected to vary among various regulator models, and even among various individual regulators of a given model. It is for that reason that regulator freeze-up is probabilistic and not deterministic.

The total probability of cold induced failure is:

$$P_f = 1 - e^{-\int_0^T r(t)\,dt} \qquad (4)$$

Dive Profiles

The risk of regulator freeze-up depends heavily on time and depth, and therefore on dive profile. Cold water SCUBA dives are restricted to no-decompression dives; that is, a diver does not have to decompress by waiting at various "stops" in the water column. There are only 17 such no-decompression (no-D) dive profiles described in the U.S. Navy Diving Manual, Vol 1, Rev. 3, 1993. It is instructive, therefore, to explore the influence of dive profile on predicted freeze-up risk for dives taken to the limits of the no-D tables.

By necessity, the prediction will be fuzzy, in that the constants a-c (Equation 3) will not be known with certainty. However, they are constrained. A combination of parameters that would result in a consistently high probability of freeze-up in shallow, short duration dives would be unrealistic, simply because that result does not match experience. Likewise, a combination that produces a vanishingly small probability of freeze-up over the course of long deep dives would be equally unsuitable.

Freeze-Up

Freeze-up is a NEDU developed computer program that simulates the whole range of "to-the-limit" no-D dives. Instantaneous risk, cumulative risk, and overall freeze-up probability is computed throughout each dive assuming a variety of values for the coefficients a and b. $\dot{V}_E$ is assumed to be elevated on the bottom compared to its value during descent and ascent.

For simplicity the coefficient c is not used. Time is an implicit factor in the overall risk, since the total risk is related to the sum of instantaneous risks. The greater the duration of the dive the greater the sum or overall risk. *Freeze-up* also allows time to be added as an **explicit** risk factor if desired, such that the effects on freeze-up probability of up to 3 coefficients (for depth, ventilation, and time) can be explored.

Table A1. Example freeze-up probabilities as a function of dive profile and coefficients a and b.

Profile	1,1 (a,b)	1,2	5,1	5,2
190/5	.06	.11	.25	.43
160/5	.05	.09	.21	.38
140/10	.07	.13	.30	.51
100/25	.10	.19	.40	.65
80/40	.12	.22	.47	.72
60/60	.13	.24	.50	.75
50/100	.17	.31	.61	.84

The *Freeze-up* predictions are surprisingly robust. The variation of risk across the various dive profiles is qualitatively invariant as the heavy work period is altered from 5 min (Table A1) to many minutes on the bottom. For a large range of coefficients, *Freeze-up* shows that the riskiest dives are the shallower, longer duration dives. There is a small reduction in risk in dropping from the 58.2 msw (190 fsw) for 5 min profile down to the 49.0 msw (160 fsw) for 5 min profile, but risk quickly rises again with the longer bottom time dives.

Implications

It may seem logical to use a no-D dive profile as a test profile for assessing the suitability of SCUBA regulators for cold water use. Unfortunately, of all the possible profiles, there is none that is clearly most appropriate. The selection of a proper testing profile becomes purely arbitrary. Is the deepest dive a worst case? Apparently not, according to Table A1. It becomes difficult to justify not using the longest shallow dive as a worst case. On the other hand, it would be truly worrisome to approve the use of a regulator to 58 msw if it had only been tested to 15 to 18 msw.

The solution to this quandary is to perform a truly worst case analysis, with a dive to the maximum depth, maximum expected ventilation rate, and for a reasonable duration. An example of such a dive is a 58.2 msw (190 fsw) dive with a 30 min duration on the bottom and a ventilation rate of 62.5 $L \cdot min^{-1}$. When such a test profile was run on *Freeze-up* with the same parameters as in Table A1, the freeze-up probabilities were 0.16, .29, .57, and .82 respectively. This compares well with the probabilities associated with the 15.3 msw (50 fsw) for 100 min profile (0.17, .31, .61, .84). Consequently, the NEDU fixed dive profile is as risky as the 100 min no-decompression profile, but the mass flow rate is much greater. The 30 min period of work is more appropriate from a thermal standpoint that the 100+ min duration of the 50 fsw for 100 min profile. *(The fixed 58.2 msw for 30 min profile is of course very unreasonable from a decompression standpoint, but that is irrelevant to this discussion.)*

For obvious reasons, the 58 msw for 30 min test is not a pass/fail test. Even the best regulators may fail the test. However, better regulators would on the average perform longer without icing than less capable regulators. Both the icing incidence and the time before icing become important parameters for ranking various regulators.

Appendix B: Modeling of Resistive Effort for the Blizzard Regulator

When the mean resistive effort values ($\overline{P}_V$) for the Blizzard regulators were compared with equivalent depth and RMV values for the Maximus regulators, the following linear relationships ($\overline{P}_{V(Blizzard)} = a + b \cdot \overline{P}_{V(Maximus)}$) were found:

a = 0.17 ± 0.06; b = 0.63 ± 0.04 for 34.5 bar supply pressure
a = 0.14 ± 0.12; b = 0.93 ± 0.09 for 103.4 bar supply pressure
a = 0.19 ± 0.09; b = 0.75 ± 0.06 for an average of both supply pressures. The coefficients for a and b represent the best estimate for the coefficient ± standard error.

The above is interpreted as follows: values for the coefficient (a) are not statistically different. On the other hand, the slope of the relationship (b) varies significantly with supply pressure. That is, the difference between the resistive effort of the Maximus and the Blizzard is the greatest at low supply pressures. Overall, with supply pressure ranging from 103.4 bar to 34.5 bar, the resistive effort for the Blizzard is roughly 75% that of the Maximus.

$\overline{P}_V$ Prediction

Resistive effort for the Blizzard regulator with 34.5 bar supply pressure varied as a function of RMV and depth in the following manner:

$$\overline{P}_V = a + [b \times (\text{depth} \times \text{RMV})^c]$$

where depth was in units of msw, and a = 0.49 ± 0.05, b = 4.04 x 10^{-6} ± 3.32 x 10^{-6}, and c = 2.17 ± 0.19 (best estimate ± standard error, Table B1).

```
R= 0.972  Rsqr = 0.944   Adj Rsqr = 0.940

Standard Error of Estimate = 0.1833

     Coefficient       Std. Error     t
a    0.49207074        0.05156611    9.54
b    0.00000404        0.00000332    1.22
c    2.17347756        0.18808826   11.56

       P          VIF
a   <0.0001      2.45
b   0.2334     619.37
c   <0.0001    594.38

Analysis of Variance:
            DF          SS            MS
Regression  2        15.809        7.9046
Residual    28        0.941        0.0336
Total       30       16.750        0.5558

                 F             P
Regression     235.2        <0.0001
Residual
Total

Normality Test:    Passed        (P = 0.0796)

Homoscedasticity Test:   Passed (P = 0.1415)

Power of performed test with alpha = 0.0500:
1.0000
```

Table B1. Statistical Summary for Non-linear Fit of Blizzard Regulator Effort to Depth and RMV.